Description

BI-DIRECTIONAL MULTI-PORT INVERTER WITH HIGH FREQUENCY LINK TRANSFORMER

BACKGROUND OF INVENTION

[0001] The field of this invention is power electronics and electrical power conversion. Electronic power inverters are devices for converting direct current (DC) power, usually from a storage battery, into alternating current (AC) power for household appliances. Some inverters also convert power from an AC source to charge the storage battery used by the inverter. Devices capable of power transfer in either direction, DC-to-AC or AC-to-DC are commonly referred to as inverter/chargers or bi-directional inverters. Inverters are also used in renewable and distributed energy systems to convert DC power from photovoltaic panels, fuel cells or wind turbines into power that can be delivered into the utility grid. There is a growing demand for an inverter product with this capability that can also

charge storage batteries and support AC loads when the utility grid is not available. Residential systems with both renewable energy sources and energy storage components typically use a battery-centric topology. This is because the battery provides a stable voltage and high peak power capabilities. In these systems, the renewable energy source interfaces to the battery through a DC-to-DC converter or charge controller to provide the required matching and regulation functions. The battery is in turn connected to a DC-to-AC inverter, to support the system loads, and to a battery charger. Additional energy sources as well as DC loads would also logically tie in at the storage battery connection point. With the present state of technology, this arrangement typically provides the most cost effective and highest performance system solution. There are a number of inherent limitations with this approach. (i) The storage battery voltages are relatively low compared to the AC voltages that the inverter produces. A common power conversion method is to convert the low DC battery voltage into a low AC voltage and then use a transformer to convert to a higher AC voltage. This approach requires a heavy, expensive, and typically inefficient, low frequency transformer. (ii) The conversion effi-

ciency from the renewable energy source to the battery to the utility grid is low because of the additive losses from each successive power conversion stage. (iii) Higher voltage, higher efficiency, lower cost photovoltaic series "string" arrays are not practical because of the photovoltaic/battery voltage disparity. (iv) Individual power converters in battery-centric systems are usually autonomous. It is advantageous for all power converters to act in concert in order to achieve optimum battery life and to better support the system loads.

SUMMARY OF INVENTION

[0002] The invention is a multi-port power electronics topology, with a high frequency transformer as the common power "conduit" and interface point for all ports. This invention would allow for energy systems that are high-frequency-transformer-core-centric as opposed to battery-centric. This invention mitigates essentially all of the limitations of battery-centric energy systems. The underlying power converter concept used for this invention was originally invented by William McMurry and disclosed in U.S. patent 3,517,300 in 1970. Since then, others have expanded the potential capabilities of these power converters but with less-than-novel or with technically obvious

variations on the original McMurry invention. The invention disclosed herein involves a number of novel power circuit topologies that allow much greater port flexibility and provide enhanced performance. The invention allows a port to perform as a boost or buck converter when sourcing power into the high frequency transformer, a capability that has not been previously established. These added capabilities allow applications to be served that would otherwise not have been practical. Also, the invention allows each non-battery port to "see" only the reflected battery characteristics at the transformer interface so that the operation of all non-battery ports are independent and non-interactive. The preferred embodiment of the invention is intended for residential electrical energy systems. There are three ports; a bi-directional battery port that allows a storage battery to source energy to the transformer or sink energy from the transformer to charge the battery, a bi-directional AC port that allows the transformer to source energy to loads and also to sink or source energy from a utility grid at unity power factor, and a renewable energy port that sources energy into the transformer and is capable of controlling the operating point of the renewable energy source and the amount of

power delivered into the transformer. Products developed using this invention will be (i) lighter because transformers operating at ultrasonic frequencies are much smaller than line frequency transformers (ii) lower cost because of the smaller transformer and the system-integrated power conversion approach and (iii) more efficient because of fewer power conversion stages and the lower core and copper losses associated with high frequency transformers. These advantages are had without sacrificing the isolation properties of a transformer.

BRIEF DESCRIPTION OF DRAWINGS

[0003] *Figure 1* illustrates the preferred embodiment of the invention, a power converter for residential energy systems having a photovoltaic (PV) array, a storage battery and a multipurpose utility/load/generator interface. *Figure 2* illustrates an alternate power converter circuit topology for residential energy systems having a renewable energy source, a storage battery and a multipurpose utility/load/generator interface. *Figure 3* illustrates the sequence of high frequency switch closures in a two-port power converter using the invention. The condition shown is a battery at the two-quadrant DC port delivering power to a load at the four-quadrant AC port.*Figure 4* illustrates the

sequence of high frequency switch closures in a two-port power converter using the invention. The condition shown is an AC voltage source at the four-quadrant AC port delivering power to (charging) the battery at the two-quadrant DC port.*Figure 5* illustrates an alternate power converter topology for residential energy systems having a renewable energy source, a storage battery and a split-phase, multipurpose, utility/load/generator interface. *Figure 6* illustrates a typical, known bi-directional semiconductor switch capable of bipolar voltage blocking, bi-directional current control and bi-directional current conduction. *Figure 7* illustrates an alternate, bi-directional semiconductor switch capable of bipolar voltage blocking, bi-directional current control and bi-directional current conduction using IGBT instead of MOSFET devices. *Figure 8* illustrates a novel, composite, bi-directional semiconductor switch capable of bipolar voltage blocking, bi-directional current control and bi-directional current conduction.

DETAILED DESCRIPTION

[0004] Figure 1 illustrates the preferred embodiment of the invention, a three-port power converter topology with one bi-directional battery port, at terminals *12* and *13*, one

four-quadrant AC port, at terminals *61* and *62*, and one unidirectional renewable energy port at terminals *84* and *85*. Two types of semiconductor switch elements are shown. Switches *21-24* and *91-93* have unipolar voltage blocking, unidirectional current control and bi-directional current conduction capabilities and are referred to as uni-directional semiconductor switches on all diagrams. Switches *41-43* have bipolar voltage blocking, bi-directional current control and bi-directional current con-duction capabilities and are referred to as bi-directional switches in all diagrams. The battery port, at terminals *12* and *13*, contains a typical, full-bridge arrangement of power switches *21-24* and is connected to winding *31* of high frequency transformer *30*. Switch pairs *21, 23* and *22, 24* are alternately closed and opened at a high rate, typi-cally greater than 20kHz, providing the transformer with square wave excitation from a relatively low impedance source. The switching is free running and the duty cycle remains fixed at 50%. The AC port, at terminals *61* and *62*, contains a typical center-tapped, half-bridge switch topology using bi-directional semiconductor switches *41* and *42*. Switches *41* and *42* are always operated syn-chronously with switch pairs *21, 23* and *22, 24* to basically

unfold the high frequency AC square wave on windings *33* and *34*. The flux in transformer *30* is always reversed at the switching frequency of bridge *20*. Unlike switch pairs *21, 23* and *22, 24*, switches *41* and *42* will operate at duty cycles from zero to 50%, as commanded by a control circuit, to provide the desired current or voltage regulation for the AC port. The inclusion of switch *43* allows the AC port to act as a boost circuit in, conjunction with inductor *51*, when delivering energy from utility grid *66* to high-frequency transformer *30*. Switch *43* also allows an efficient path for freewheeling inductor current when power is being delivered from transformer *30* to AC loads *64* or utility grid *66*. Without switch *43*, a limited boost function can be had by simultaneously closing switches *41* and *42*, causing transformer windings *33* and *34* to be short-circuited, and opening all bridge *20* switches. This works well for two-port converters but limits the transformer availability for converters with three or more ports because the transformer is unable to sink or source power at any port when windings *33* and *34* are shorted. Also, anytime bridge *20* is not in conduction, the operation of one port becomes dependent on the operation of other ports and the value of this power conversion approach is

severely compromised. The inclusion and function of switch *43* in the AC port is novel and part of this invention. It should be noted that if power is flowing into the AC port, inductor *51* acts as a boost inductor, if power is flowing out of the AC port, inductor *51* acts as a filter component in conjunction with capacitor *52*. The renewable energy port, at terminals *84* and *85*, provides the ability for the converter to track the maximum power point of photovoltaic (PV) array *83* under various ambient conditions. The basic function of the port is that of a buck regulator. Energy from PV array *83* is stored in capacitor *55*. Unidirectional switch *93* is turned on and off at a rate typically greater than 20kHz and with a duty cycle established by a control circuit to regulate the PV voltage and/or power. When switch *93* is closed, diode *71* is back-biased and current flows through boost inductor *56* and returns through either transformer winding *37* and unidirectional switch *91* or through transformer winding *38* and unidirectional switch *92*. When PV energy is available, switches *91* and *92* always operate at 50% duty cycle and in tandem with switch pairs *22, 24* and *21, 23* respectively. When switch *93* is opened, the freewheeling inductor current is conducted through diode *71* and either transformer

winding *37* and unidirectional switch *91* or transformer winding *38* and unidirectional switch *92*, whichever path is active at the time. The three-switch buck port topology described here is novel and is part of this invention. Figure 2 illustrates an alternate topology for the renewable energy port, at terminals *84* and *85*. The basic function of the port is that of a boost regulator. In the preferred embodiment, the renewable energy source is either fuel cell *81* or DC generator *82*. Energy from the renewable source is stored in capacitor *55*. Unidirectional switch *93* is turned on and off at a rate typically greater than 20kHz and with a duty cycle established by a control circuit to regulate the port voltage and/or power. When switch *93* is closed, current flows from capacitor *55* to charge inductor *56*. When switch *93* is opened, the current flowing in inductor *56* is conducted through diode *71* and either transformer winding *37* and unidirectional switch *91* or transformer winding *38* and unidirectional switch *92*, whichever path is active at the time. Switches *91* and *92* operate at 50% duty cycle and in tandem with switch pairs *22, 24* and *21, 23* respectively,but may also be switched off when switch *93* is on. The three-switch boost port topology described is novel and is part of this invention. Figure 3 illustrates one

method of synchronizing the battery port and AC port switching elements to convert power from a storage battery to supply household AC loads. In this mode, AC voltage is regulated across the load. Regulation methodologies are known and typically use voltage and current feedback, reference values and error amplifiers to implement a fast inner current control loop and a slower outer AC voltage regulation loop. Figure 3 illustrates the sequence of a complete high frequency switching cycle at point in time where a small portion of the positive voltage half-sine across the load is being created. In Figure 3A, switch *41* is closed simultaneously with bridge pair *21, 23* causing current to flow out of the battery and into the load in the direction shown. In figure 3B, switch *41* is opened, interrupting the current flow from the battery, and at the same time switch *43* is closed. Switch *43* acts as a freewheeling diode to provide a path for the inductor current. In Figure 3C, bridge pair *21, 23* are opened and bridge pair *22, 24* is closed, at the same time switch *43* is opened and switch *42* is closed. Current still flows through the load in the same intended direction even though the flux in the transformer has reversed. In Figure 3D, switch *42* is opened, interrupting the current flow from the bat-

tery and at the same time switch *43* is closed, again providing a path for the inductor current. The sequence is then repeated 3A, 3B, 3C, 3D, 3A, etc. The ratio of switch *41* and *42* "on" times to the switching period controls the amount of energy transferred and is effectively the PWM duty cycle controlled by the regulator. The selection of switch *41* verses *42* controls the polarity of the voltage delivered to the load. The alternation of switch pairs *21*, *23* and *22*, *24* at high frequencies enable the use of a high frequency transformer. Figure 4 illustrates one method of synchronizing the battery port and AC port switching elements to convert power from the AC utility grid to charge the storage battery. In this mode, AC current is sourced from the utility grid at unity power factor. The amplitude of the sine wave current out of the utility is proportional to the instantaneous battery charge current commanded by the system controller's charge algorithm. Regulation methodologies are known and typically use voltage and current feedback, reference values and error amplifiers to implement a current control loop with a sinusoidal current reference that is synchronous with the AC line voltage. Figure 4 illustrates the sequence of a complete high frequency switching cycle at point in time where a small por-

tion of a positive current half-sine is being sourced from the utility grid. In Figure 4A, switch *43* is closed and the inductor charges from the instantaneous utility line voltage. Bridge pair *21, 23* is closed but the states of the bridge pairs are irrelevant because switches *41* and *42* are both open. In Figure 4B, switch *43* is opened and switch *41* is simultaneously closed. The inductor current flows into the transformer. In Figure 4C, bridge pair *21, 23* are opened and bridge pair *22, 24* is closed, at the same time switch *41* is opened and switch *43* is closed, charging the inductor. In Figure 4D, switch *43* is opened and switch *42* is simultaneously closed and current is again delivered to the transformer. The sequence is then repeated 4A, 4B, 4C, 4D, 4A, etc. The ratio of switch *43* "on" time to switch *41* and *42* "on" times controls the energy transferred. The transformer turns ratio is such that the battery cannot be charged from the utility grid under normal conditions without the boost circuit. The selection of switch *41* verses *42* is selected based on the instantaneous AC line polarity. In this battery charging mode, switch *43* provides a boost regulator function and switch pairs *21, 23* and *22, 24* operate as synchronous rectifiers. Figure 5 illustrates two AC ports configured for interface to a split-phase utility or to

deliver power to split-phase loads. Figure 6 illustrates one method for configuring a switch element with the required characteristics for use as switches *41*, *42* and *43* as referencedin Figure 1. Terminals *11* and *12* are the switch poles. The two terminals are interchangeable with respect to any polarity reference. MOSFETs *7* and *8* are connected in a common source configuration so that voltage can be blocked in either direction and current flow can be controlled in either direction. Gate driver *4* drives MOSFETS *7* and *8* through resistors *5* and *6* respectively. MOSFETs *7* and *8* are switched simultaneously. The Vcc *2* to Vss *3* power supply and the logic drive signal *1* are electrically isolated from the other switch elements in a typical power converter. A number of MOSFET devices may be paralleled so that the conduction voltage drop of the MOSFET is always lower than the conduction voltage of the MOSFET parasitic diode. As such, current never flows through the MOSFET parasitic diodes. The configuration shown in Figure 6 is known. Figure 7 illustrates a second method for configuring a switch element with the required characteristics for use as switches *41*, *42* and *43* in Figure 1. The method is essentially the same as shown in Figure 6 except that Insulated Gate Bipolar Transistors (IGBTs) are

used in place of FETs. This logical extension is obvious and therefore considered known by default. Figure 8 illustrates a hybrid switch that incorporates the best features of both the MOSFET and IGBT bi-directional switches and is the preferred method for configuring a switch element with the required characteristics for use as switches *41*, *42* and *43* in Figure 1. Terminals *13* and *14* are the switch poles. The two terminals are interchangeable with respect to any polarity reference. IGBTs *9* and *10* are connected in a common emitter configuration and each are connected in parallel with MOSFETs *11* and *12* respectively. Voltage can be blocked in either direction and current flow can be controlled in either direction. Gate driver *4* drives all semiconductor devices through gate resistors *5-8*. The Vcc *2* to Vss *3* power supply and the logic drive signal *1* are electrically isolated. In higher voltage applications, the hybrid switch illustrated in Figure 8 operates with lower losses over a wider range of currents than either the MOSFET only or the IGBT only bi-directional switch. MOSFET devices exhibit a resistive "on" characteristic while IGBT devices exhibit a semiconductor junction "on" characteristic. In the AC port application discussed, the IGBT devices handle the high peak currents more cost effectively than

the MOSFET devices. High peak currents are shunted from the MOSFETS by the IGBTs. At lower currents, the current is shunted from the IGBTs and parasitic MOSFET diodes by a MOSFET "on" resistance that represents a lower voltage drop than the semiconductor "on" voltage. Additionally, if separate drivers are used for the IGBTs and the MOSFETs, the MOSFET turnoff can be delayed with respect to the IGBT turnoff to take advantage of the faster MOSFET switching speeds. This bi-directional hybrid switch is novel and is part of this invention.